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Strength Improvement of Dredged Soil Through Solidification by Eaf Slag-Based Geopolymer

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Summary

Some investigations to improve the strength of soft soil had successfully conducted by way of solidification using fly ash as prime material for geopolymer. EAF slag, a byproduct from the process of producing steel, had been used as prime material of geopolymer in process of solidification to improve the strength of dredged soil. In this research, the effect of EAF slag-based geopolymer for strength improvement of dredged soil is studied through the following states: (i) the relationship between the compressive strength and the curing period, and (ii) the relationship between the unconfined compressive strength and the mixture ratio. The research giving results as follow: (i) Mixing the dredged soil with geopolymer has increased the strength from the strength of medium soil to the strength of hard soil as increasing the mixture ratio of soil-geopolymer. (ii) The improvement of strength is significantly affected by the mixture ratio ($p<0.05$) rather than the curing period ($p>0.05$).

Key words: EAF slag, geopolymer, solidification, unconfined compressive strength

Introduction

From the engineering point of view, the dredged soil can be classified as a very soft geo-material with limited strength and higher water content. In order to provide the improved strength of dredged soil, many methods are available, including the solidification method by the geopolymer. Geopolymer, first introduced by Joseph Davidovits, has been widely examined and reviewed by many researchers, due to the fact that the geopolymer suppress CO_2 emission since its process emits only 20% of CO_2 compared to Portland cement process [2]. The formation of geopolymer is caused by the reaction of an aluminosilicate powder with an alkaline silicate solution at roughly ambient condition. Later geopolymer is solidified by polymerization, as the metal ion, liquated out from the filler, bridges the acetic acid silicate by the reaction with the components of water glass, such as silicate (Si), oxygen (O) and hydrogen (H) [3]. The solidification method by geopolymer to improve the strength of soft soil had been investigated previously by using fly ash as the prime material [4,9,11]. However there are several materials that consumable as a prime material, such as coal ash, slag and rice hush ask. This research has used the Electric Arc Furnace (EAF) slag as the prime material of geopolymer to solidify the

dredged Goumeki soil. The objective of the research is to study the effect EAF slag-based geopolymer for strength improvement of the dredged Goumeki soil through the relationship between the unconfined compressive strength (q_u) and both the curing period (t) and the mixture ratio (δ).

Materials and Methods

1. Soil

Goumeki soil, dredged from a water pond in Karatsu at Saga prefecture, was used as the soil sample. From the soil properties experiment (JIS), the dredged Goumeki soil has a high natural water content which is 92 % and a high liquid limit which is 113.9 % as well (Table 1). This soil is mostly being composed by clay and colloid.

Table 1. Physical and chemical properties of dredged Goumeki soil

Properties	Value	Properties	Value
Natural Water Content, w (%)	92	Atterberg Limits :	
Density of Soil Particles, ρ_s (g/cm^3)	2.62	liquid limit, w_L (%)	113.9
Particle Size Distribution (%) :		plastic limit, w_P (%)	38.7
coarse sand (0.85 mm - 2 mm)	−	plasticity index, I_P	75.2
medium sand (0.25 mm - 0.85 mm)	−	Ignition Loss, L_i (%)	10.3
fine sand (0.075 mm - 0.25 mm)	20.7	pH (H_2O)	4.4
silt (5 μm - 0.075 mm)	16.3	Electric Conductivity, χ (mS/cm)	2.3
clay (2 μm - 5 μm)	20.4	Cation Exchange Capacity, CEC (cmol/kg)	28.0
colloid (< 2 μm)	42.6		

2. Prime material

Slag is the solid waste generated during the metallurgical process of extraction and refining steel. Slag consists predominantly of oxides and silicates of magnesium, calcium, aluminum, iron etc. The Electric Arc Furnace (EAF) slag is used as the prime material. The main chemical constituents of EAF slag depends significantly on the properties of the recycled steel. Typically, the FeO, CaO, SiO_2, Al_2O_3, and MgO contents of EAF slags are in the 10−40%, 22−60%, 6−34%, 3−14% and 3−13% ranges, respectively. Other minor components include other oxidized impurities, such as MgO, MnO, and SO_3. EAF slag also contains free CaO and MgO along with other complex minerals and solid solutions of CaO, FeO, and MgO. The FeO content of EAF slag generated from stainless steel production process can be as low as 2% [10]. The EAF slag in the research was supplied from a local stainless company in Yamaguchi prefecture (Table 2). This slag has high calcium, which is 48.6 % of total mass. The silicon and aluminum of slag constitute about 32% of total mass. Fig. 1 shows image of the EAF slag surface produced by the scanning electron microscope (SEM). This image shows irregular shapes of surface of EAF slag with some flair and blunt edges, and the larger chunks are surrounded by smaller chunks.

Table 2. Chemical composition of EAF slag

Component	Composition	Component	Composition
Cu	< 0.01 %	Fe_2O_3	1.01 %
Zn	< 0.01 %	P_2O_5	0.01 %
Pb	2 mg/kg	TiO_2	1.54 %
Hg	< 1 mg/kg	SO_3	0.43 %
CaO	48.16 %	Cd	< 1 mg/kg
SiO_2	26.73 %	Cr_2O_3	2 %
Al_2O_3	5.32 %	Cl	< 0.01 %
MgO	5.47 %	CN	< 1 mg/kg
Na_2O	0.02 %	Water Content	20.2 %
K_2O	0.02 %	Ignition Loss	5.0 %

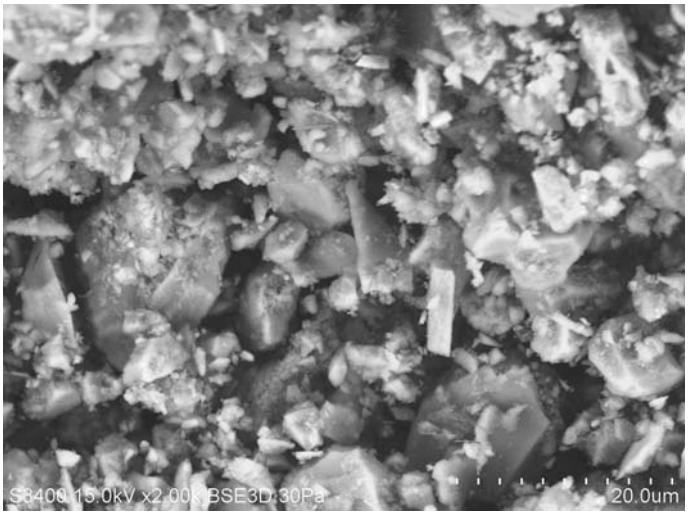

Fig. 1. SEM image of EAF slag

3. Foaming agent

Sodium bicarbonate or sodium hydrogen carbonate is the chemical compound with the formula $NaHCO_3$. Sodium is a white solid that is crystalline but often appears as a fine powder. Sodium bicarbonate is an amphoteric compound. Aqueous solutions are mildly alkaline due to the formation of carbonic acid and hydroxide ion. Sodium bicarbonate has been used widely in many applications. In manufacturing geopolymer, sodium bicarbonate is used as a foaming agent to control porosity of geopolymer paste and to shorten the diffusion distance for entrapped water to leave the sample [1].

4. Activator

For the activator, this research has used the liquid alkaline activator by mixing sodium silicate and sodium hydroxide [5].

a. Sodium silicate

Sodium silicate is the common name for a compound sodium metasilicate, Na_2SiO_3,

also known as waterglass or liquid glass. It is available in aqueous solution and solid form. It is stable in neutral and alkaline solution. In acidic solution, the silicate ion reacts with hydrogen ion to form silicic acid, which when heated and roasted forms silica gel, a hard and glassy substance. Waterglass is rarely used as an independent activating unit, because it does not possess enough activation potential to initiate pozzolanic reaction alone. Rather, it is commonly mixed with NaOH or KOH as a fortifying agent to enhance alkalinity and increase overall specimen strength. The most used alkaline activator in geopolymerization is a mixture of sodium or potassium hydroxide (NaOH, KOH) with sodium waterglass ($n SiO_2 Na_2O$) or potassium waterglass ($n SiO_2 K_2O$) [6,7]. In this research, commercial sodium silicate No. 3 was used. The numbering of this sodium silicate is based on the Japanese Industrial Standard (Table 3).

b. Sodium hydroxide

Sodium hydroxide, also known as caustic soda, is an organic compound with the chemical formula NaOH. It is a white solid, highly caustic metallic base and alkali salt. It is available in pellets, flakes, granules and as a 50% saturated solution. Sodium hydroxide is soluble in water, ethanol and methanol, also adsorbs moisture and carbon dioxide in air. Sodium hydroxide is commonly used as an alkaline activator in geopolymer production. It is also used as a combination with potassium hydroxide or sodium silicate in geopolymer production [8]. The 18 M of commercial sodium hydroxide solutions was used in the research.

Table 3. Chemical Composition of Sodium Silicate (JIS K 1408-1966)

Classification / Item	Sodium Silicate No. 1	Sodium Silicate No. 3
Appearance	Colorless or light color liquid like starch syrup	
SiO_2 (%)	35 − 38	28 − 30
Na_2O (%)	17 − 19	9 − 10
Fe (%)	0.03 max	0.02 max
Water-insoluble matter (%)	0.2 max	0.2 max

5. Experimental works

The research involved experimental works in the laboratory according to the following sequence: (i) soil properties experiment; (ii) mix design; (iii) mixing soil and geopolymer; (iv) curing of specimen; (v) testing of specimen, and (vi) analysis of the results. The soil properties experiments were conducted based on the Japanese Industrial Standard (JIS) and the Japanese Geotechnical Society (JGS) standard procedures. The experiments were aimed to determine water content of soil, density of soil particles, particle size distribution of soil, liquid limit and plastic limit of soil, ignition loss of soil, pH of suspended soil, electric conductivity of soil and cation exchange capacity. The results of soil properties experiments are read more in the Table 1.

In the mix design, the composition of geopolymer paste made of EAF slag as the prime material, sodium bicarbonate as the foaming agent, and sodium silicate and sodium hydroxide as the liquid activator was calculated. The mixture ratio of soil-

geopolymer was determined in the mix design as well. To make the geopolymer paste, it depends on the water content of the geopolymer. In the experiment of geopolymer, water content is important to achieve optimum result [6]. This experiment had designed the water content of geopolymer to be 40%. It was determined as the percentage of the weight of liquid activator to the weight of the solids, consists of EAF slag and sodium bicarbonate. The ratio 1:2 is as the ratio of sodium hydroxide to sodium silicate in the composition of liquid activator. The amount sodium bicarbonate is 5% of the weight of the EAF slag. The mixture ratio of soil-geopolymer in the experiments was set to be 75% soil − 25% geopolymer (δ = 25%), 50% soil − 50% geopolymer (δ = 50%) and 25% soil − 75% geopolymer (δ = 75%). For soil and pure geopolymer, the mixture ratio are δ = 0% and δ = 100% respectively. In the mixing part, the geopolymer paste was prepared first

Fig. 2. Curing of specimens

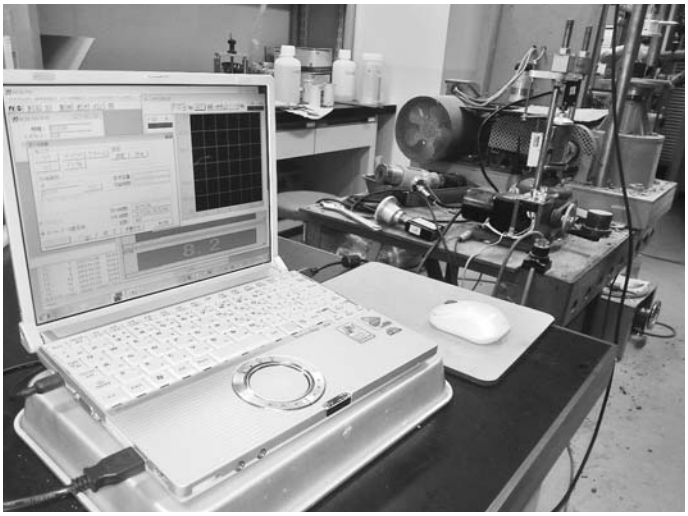

Fig. 3. Testing of specimens

Table 4. Result and condition of experiment

Soil (%)	Slag based Geopolymer (%)	Weight (g)					Water Content (%)	q_u (kPa) at curing period		
		Soil	Slag	$NaHCO_3$	Sodium Silicate 3 (SS3)	NaOH		7	14	28
25	75	750	1531	77	429	214	35	336	1058	1223
50	50	1500	1020	51	286	143	56	107	155	169
75	25	2250	510	26	143	71	59	54	56	59
0	100	0	2041	102	571	286	40	895	953	1465

prior to mixing with the soil. The solids (EAF slag and sodium bicabornate) and the liquids (sodium silicate No. 3 and 18 M sodium silicate) were mixed separately before combined to form geopolymer mortar. The water content of the soil was adjusted to its obtained liquid limit prior to mixing with geopolymer paste.

The mixed of soil-geopolymer was compacted in a cylindrical PVC mold (40 mm × 100 mm), and was kept in humid conditions for 7 days, 14 days, and 28 days prior to testing to observe the development of strength (Fig. 2). In the testing of specimen part, the unconfined compression test device was functioned to determine the unconfined compressive strength of the specimens (Fig. 3). In the analysis of the results, statistical analysis was used to assist in drawing a conclusion according to the objective of the result (Table 4).

Results and Discussion

When geopolymer was mixed with soil at δ = 25%, the gained strength belonged to the typical strength of medium soil (50-100 kPa). As the ratio increased to δ = 50%, the gained strength belonged to the typical strength of stiff soil (100-200 kPa). The significant increasing was achieved at the δ = 75% where the gained strength belonged to the typical strength of very stiff soil (200-400 kPa) at 7 days, and hard soil (>400 kPa) at 14 days and 28 days (Fig. 4). Though each designated mixture ratio presented different strength which lead to different consistency as well, their strength is gained within seven days of curing period. This also denotes that the effect of EAF slag-based geopolymer to solidify soil took place within a week since mixing. Regarding to curing concern, previous investigations in soil solidification have reported that the strength of solidify soil developed during curing period [4,9]. Similar result has been obtained within this research. Some past investigations has reported that curing temperature effects to development and reduction of strength of geopolymer [6]. The whole experiments in this research maintained the specimens in humid conditions to minimize temperature difference of ground and soil, which means that the temperature of curing was lower temperature. Although the curing temperature is not the objective of the study, but at lower temperature the solidified soil has developed its strength, including the geopolymer (ratio of 100 %).

From the F-test it is found that the mixture ratio provides a significant effect (p<

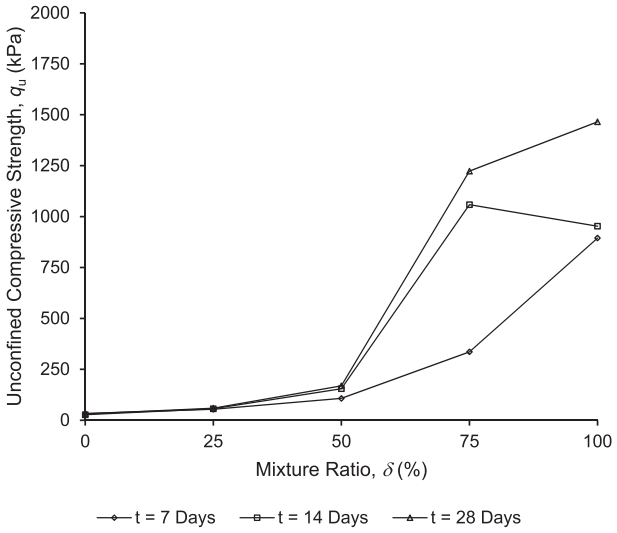

Fig. 4. Relationship between q_u and δ

Table 5. *F*-test values for mixture ratio and curing period

Subject	Source of variation	*F* test value	*p*	Remarks
Unconfined Compressive Strength (q_u)	Mixture ratio (δ)	9.03	<0.05	*
	Curing period (t)	1.19	>0.05	ns

Table 6. Linear equations among mixture ratio, curing period and unconfined compressive strength, and their correlation coefficient

Subject	Equation	Correlation Coefficient (r)
Unconfined Compressive Strength (q_u) and mixture ratio (δ)	$q_u = 152.78 + 1.7421\delta$	1.000
Unconfined Compressive Strength (q_u) and curing period (t)		
at δ = 25 %	$q_u = 52.29 + 0.26t$	0.988
at δ = 50 %	$q_u = 100.10 + 2.67t$	0.882
at δ = 75 %	$q_u = 253.54 + 37.89t$	0.859

0.05) to the unconfined compressive strength of the dredged Goumeki soil by EAF slag-based geopolymer, whereas the curing period provides a non-significant effect (p>0.05) to the unconfined compressive strength of the dredged Goumeki soil by EAF slag-based geopolymer (Table 5). Moreover, the equations to determine the unconfined compressive strength of the treated dredged Goumeki soil by EAF slag-based geopolymer along with their correlation coefficient to determine their relationship based on the results of experiments were established as well (Table 6).

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EAF スラグをベースとしたジオポリマーを用いた浚渫粘土の固化による強度向上

ロスキ　ローランス　イザック　レグランス*・近藤　文義**
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平成26年11月13日　受理

要　　旨

フライアッシュをベースとしたジオポリマーによる軟弱粘土の固化に関する幾つかの成功事例がこれまでに報告されている。本研究は、フライアッシュと同様の産業廃棄物であるステンレス製鋼スラグ（EAF スラグ）をベースとしたジオポリマー（スラグ・ジオポリマー）による浚渫粘土の強度向上について検討したものである。スラグ・ジオポリマーによる浚渫粘土の強度向上に関して、(i)一軸圧縮強度と材齢の関係、および(ii)一軸圧縮強度と配合比の関係について検討した。主な結果は以下の通りである。(i)ジオポリマー改良による浚渫粘土の圧縮強度は、土・ジオポリマーの配合比が大きくなるにつれて普通粘土から硬質粘土へと増加した。(ii)改良の効果は材齢の影響による有意差は認められず（$p>0.05$）、配合比によって有意差が認められた（$p<0.05$）。